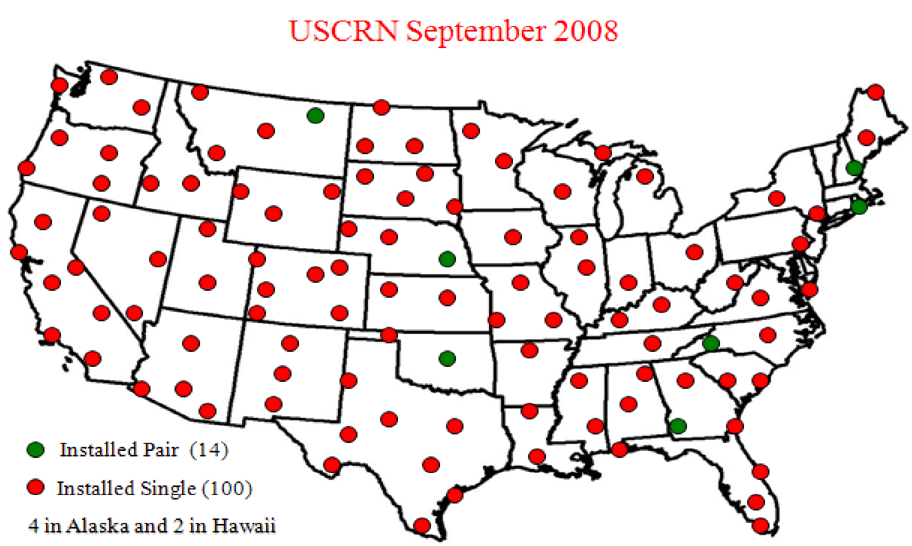
Soil Moisture and Soil Temperature Observations and Applications:
A Joint U.S. Climate Reference Network (USCRN) –
National Integrated Drought Information System (NIDIS) Workshop
Oak Ridge, TN, March 3-5, 2009

Workshop Summary

The workshop was convened by Bruce Baker (NOAA/NESDIS/NCDC) and Tilden Meyers (NOAA/OAR/ATDD) to provide a forum for discussing issues related to the installation of soil moisture, soil temperature and relative humidity instruments for the USCRN stations in FY09-11. The goal of the workshop was to gain knowledge and information from existing networks, determine an optimal configuration (depths, replication, placement), discuss products and user data needs for operations and research, understand ancillary data and metadata options (*e.g.*, soil classification, infiltration rates, etc.), refine QA/QC procedures, review sampling protocols, explore the idea of a soil moisture/temperature testbed, and address the issue of station representativeness for the remote sensing and modeling communities.



I. Participation

The attendees of the two-day workshop included experts in operating state and national networks, remote sensing, soil moisture/temperature measurements, and soil scientists.

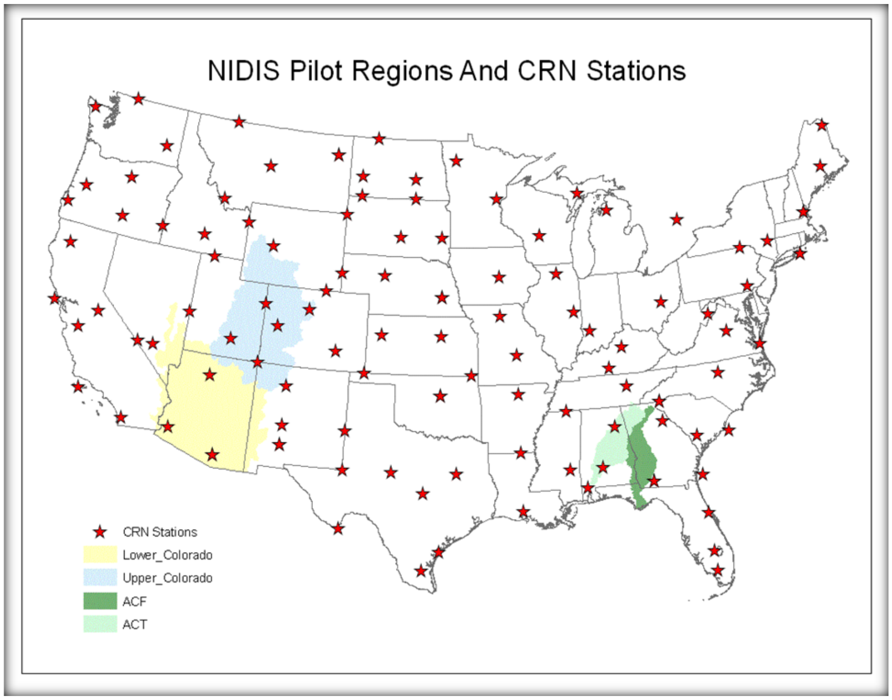
The attendees were: Tilden Meyers (NOAA/OAR), Bruce Baker (NOAA/NESDIS), Michael Palecki (NOAA/NESDIS), Chris Fiebrich (U. Oklahoma), Mike Brewer (NOAA/NESDIS), Gary Schaefer (USDA/NRCS), Robert Scott (U. Illinois), John Fitzmaurice (Agri-Food Canada), Ana Pinheiro (STG), Thomas Jackson (USDA/ARS), Michael Cosh (USDA/ARS), Alan Robock (Rutgers U.), James Verdin (USGS), Yunyue Yu (NOAA/NESDIS), Peter van Oevelen (GEWEX), Steve Oncley (NCAR), Brian Fuchs (NDMC), Eric Hunt (NDMC), Xiwu Zhan (NOAA/NESDIS), William Collins (consultant), Robert Zamora (NOAA/OAR), Debra Harms (USDA/NRCS), Chad McNutt (NOAA/OAR/CPO), Mark E. Hall (ORAU), Andrea Fey (NCDC/STG)**,** and Egg Davis (NCDC/STG).

II. Program Overviews

Tilden Meyers opened the workshop with a brief overview of the agenda, meeting objectives, and a general list of questions to be addressed. First on the agenda for day 1 were talks providing an overview of current national and state networks, current and future needs for soil moisture and soil temperature data, and the international perspective for this information from the International GEWEX Program Office and Agriculture Canada.

Michael Palecki presented an overview of the USCRN network and its current configuration. Deployment of 114 stations distributed across the continental U.S. was completed in 2008 using station design and data processing procedures following the Ten Principles for Climate Monitoring. The program is now developing products for the climate community, including hourly and daily quality controlled data that are available by ftp. The program is now looking to add soil moisture, soil temperature and relative humidity sensors to most of the stations during 2009 – 2011. New directions in research include supporting NIDIS with the soil moisture, soil temperature, and relative humidity measurements, calibration and validation for remote sensing, and new climate monitoring products.

Mike Brewer gave an overview of the National Integrated Drought Information System (NIDIS) and US Drought Portal. NIDIS consists of 5 components: early warning, education, mitigation, portal, and monitoring capability. Drought impacts due to natural variability are of course modified based upon societal changes: population increase, growth of cities, and the movement of population to areas prone to water stress.



The NIDIS desired products from the USCRN program are:

- Maps of soil moisture/temperature and anomalies,
- Verification of existing soil moisture from models including LDAS,
- Surface energy budgets,
- Timing of spring runoff, and
- Merger with other SM/ST networks for a sub-national analysis.

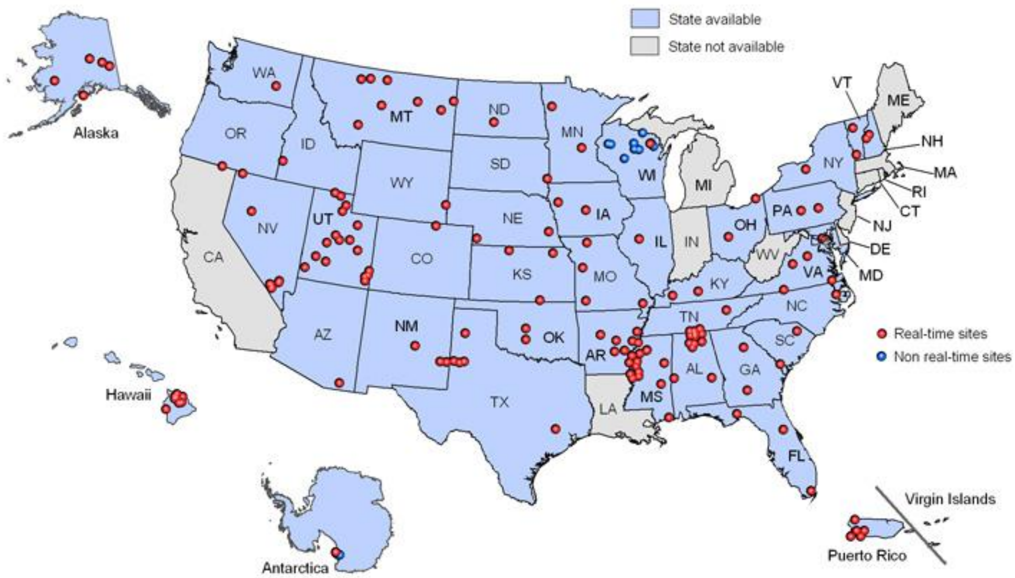
Peter Van Oevelen discussed the activities of the International Soil Moisture Working Group (ISMWG). Soil moisture is regarded as an emerging key variable by the Global Climate Observing System (GCOS) and considered to be important in land surface feed backs. Temporal changes are viewed to be as important as spatial representation for *in situ* soil moisture/soil temperature measurements. The ISMWG promotes international cooperation in research and applications in support of soil moisture satellite missions and the development of an *in situ* global soil moisture network.

Alan Robock gave an overview of the Global Soil Moisture Bank. The Global Soil Moisture Data Bank is a web site that provides *in situ* soil moisture observations at no cost and is dedicated to collection, quality control, and distribution of soil moisture data for use in land surface modeling, remote sensing, and data analysis. There are two scales of soil moisture variability. The local scale is related to the small scale variations of soil and vegetation and is the scale most familiar to hydrologists. The regional scale is controlled by large-scale atmospheric processes and is the scale of concern to climatologists. Both scales must be measured and understood in order to accurately model or remotely sense soil moisture.

John Fitzmaurice provided a Canadian perspective on improved soil moisture measurements. The enhanced measurements would support modeling systems that provide early warning of extreme weather events such as flood, enhancing human safety, and reducing risk of water contamination. A better understanding of water resources as it relates to water availability would also be important, which is consistent with emerging thoughts from the Deputy Ministers' Committee on Economic Prosperity, the Environment and Energy. It is a key priority of this interdepartmental working group to better understand and predict water availability.

III. Network Overviews /Remote Sensing

Gary Schaefer gave an overview of the USDA/NRCS Soil Climate and Analysis Network (SCAN). Currently the network has 151 stations in 39 States and measures soil moisture and soil temperature at levels of 2, 4, 8, 20, and 40 inches below the surface.



There will be an additional 33 new scan stations added to the network in FY09:

- 16 in Utah
- 4 in New Mexico
- 10 in Alabama
- 1 in Idaho
- 1 in Nevada
- 1 in California

Chris Fiebrich gave an overview of the Oklahoma Mesonet soil temperature and soil moisture networks and some of the quality control measures that are currently implemented. After installation, soil moisture data are manually flagged for 21 days to allow the soil to heal (sometimes longer during extended drought periods). QA/QC procedures include range tests, calibration tests, step tests, frozen soil tests, and preferential flow tests. Manual inspection and time series analysis of maximum and minimum for each depth are performed monthly. Soil temperature automated tests include range, step, persistence, spatial, like-instrument, heat transfer, climate, and various adjustment tests. Manual analysis includes looking at plots of average values and cumulative differences between sensors at different depths. Soil temperature observations are obtained beneath both bare and naturally sod soil at most sites.

Eric Hunt discussed the soil moisture monitoring, data, and products in Nebraska. A key point was the development of a soil moisture index that is based on continuous soil moisture measurements, allowing them to detect drought stress. The index is based on three known quantities, field capacity, wilting point, and current volumetric water content. The field capacity and wilting point are determined through field observations.

Tom Jackson discussed the role of soil moisture/climate networks in validation of the Soil Moisture Active and Passive (SMAP) satellite mission. Critically important for remote sensing validation are ground based networks providing actual quantitative soil moisture observations to evaluate algorithm performance. Recommendations included:

- Continue/establish a number of dedicated soil moisture validation sites
- Develop techniques for scaling sparse networks to footprints
- International cooperation
- Ease of access and complete archiving of suitable validation data
- Address similar issues with freeze-thaw (temperature) and SM profiles

Ana Pinheiro provided an overview of the International Workshop on the Retrieval and Use of Land Surface Temperature (LST): Bridging the Gaps. The ideal LST validation site should be a homogeneous (or a well characterized heterogeneous area) at the scale of a satellite pixel and the point measurements should be representative of a larger area. There should be adequate temporal frequency (15 min preferred; 30 min acceptable; 5 minutes ideal), availability of co-located (time and space) ancillary data (surface fluxes, met data, soil profiles, vegetation properties, etc), measurement redundancy (ideally more than one sensor), detailed site characterization, and metadata.

Xiwu Zhan discussed the values of ground network observations in development of satellite soil moisture data products. The current satellite soil moisture data quality was compared with SCAN and USDA-ARS Vitel network soil moisture measurements. This revealed the importance of intensive field campaigns to characterize site representation to satellite footprints, the importance of surface temperature observation for satellite soil moisture retrieval algorithms, and some issues for consideration in setting up USCRN soil moisture and soil temperature sensors.

Bob Yu discussed attempts to evaluate satellite LST using SURFRAD data.

- Match-up dataset of satellite and ground data was created carefully
- Direct comparisons indicate promising algorithm accuracy
- Correlation analyses showed good algorithm precision
- Further work will be performed using three-measurement comparison

IV. Measurements & QA/QC

Bruce Baker discussed the integration of soil moisture/soil temperature and relative humidity measurements into the USCRN stations. The addition of these sensors will improve the understanding of the water budget, improve the modeling of soil moisture, and provide additional sites for calibration/validation of remote sensing techniques. The important factors in providing climate quality measurements for these parameters include, metadata, standard installation procedures, adequate sampling protocols, and engaging the remote sensing community to participate in any intensive campaigns for determine the representativeness of the point measurements for a larger area.

Tilden Meyers provided insight into the performance of the soil moisture/soil temperature probes that have been selected for use in the USCRN. Repeatability was better than expected with standard deviations of about +/- 0.1°C. Overall accuracy seemed acceptable from -20°C to 40°C, but larger excursions were observed at the range limits of the probe. Probe-to-probe range was about 0.3°C, with larger differences at the extremes.

William Collins presented an analysis of the probes in the ATDD test bed at the nearby University of Tennessee Arboretum. There were 4 plots and each plot had three sensors co-located at 5 & 10 cm, two sensors at 20 cm and one sensor at 50 & 100 cm. The inter-sensor comparisons show wide differences in the performance of individual sensors. Also, there are significant differences between the mean values of moisture at the 4 holes at 5 and 10 cm depths. The results have implications for quality control for both temperature and moisture:

- The use of 3 sensors is invaluable for error and value determination.
- Sensor value and change in time are both useful for QC.
- Individual sensor characteristics, if developed, might be valuable.

Mike Cosh (USDA/ARS) gave a presentation on validating large scale networks using temporary local scale networks for remote sensing purposes. The goal of this type of study is to provide a *close approximation* of soil moisture within the area and depth measured by low frequency passive microwave sensors. This would result in a robust data set for validating retrieval algorithms as well as models for the AMSR-E Soil Moisture Products. It has been established in these examples that small networks are capable of accurately estimating large scale soil moisture averages using intensive short term field campaigns and temporal stability analysis. This analysis also identifies suspicious soil moisture stations and representative stations for eventual reduction of local networks to fewer or single points.

Steve Oncley discussed the current measurement capabilities and those being developed at NCAR. In particular, current technologies for observations of soil moisture and soil temperature sensors at NCAR were discussed. Typically the deployment of stations is for a short duration field season up to 8 weeks. They now have 10 stations to deploy for a study that can characterize heterogeneous surfaces. They plan to expand this network to 100 stations. The advantages of this suite of systems is ease of deployment, lower power, wireless data transfer, lower weight/size, and lower footprint (for site permission). The soil sensors are used to understand the energy budget and hydrology. For soil moisture, they are using Echo-5 sensors, but complement this with Hukseflux thermal properties probes to obtain the moisture content of frozen soils.

Robert Zamora discussed a new soil moisture observational network that is being used in support of NOAA's hydrometeorological testbed. Preliminary results suggest that the soil moisture observations will play an important role in the evaluation and development of the NWS hydrological models. This is of importance for flash flood event warning. In addition there could be improvements in meteorological weather prediction model land surface and boundary layer parameterizations, and assessments of the impact of climate change on our water supply with this new network.

Robert Scott discussed the Illinois Soil Moisture network. The neutron probe data spans from 1983-2004 (through 2008 at 8 sites) and the capacitance probe data started in 2002-present using the Stevens Hydra A probe. The data indicate that there is an increasing inter-site soil moisture variability with depth, ranging from ±3% near the surface year-round to ±6% in winter and ±10% during the growing season in the deepest layer. There seems to be a strong connection in deeper layers at sites with low surface terrain slope and high soil moisture content, and vice versa.

V. Considerations for the Deployment of Soil Moisture/Soil Temperature and Relative Humidity Instruments at the USCRN Stations in FY09-11, Based on Workshop Discussion Sessions

SOIL PROBE INSTALLATION

1) Soil instrument placement consensus

    The three sets of soil probes should be placed in three separate plots around the tower, at the depths 5, 10, 20, 50, and 100 cm.

2) Instrument installation

    At each plot, one hole should house the vertically embedded 100 cm level probe, and another hole should house the 5, 10, 20, and 50 cm probes mounted horizontally.

3) Site configuration of plots

    a) Avoid existing trenches and other areas of disturbed or compressed soils.
    b) Run a 3-conducter wire from the data logger to a junction box using copper tubing as conduit towards each soil probe plot. These places can be 3-10 m away from the tower.
    c) If a junction box is used, it should not be close enough to shadow the soil measurement plot.
    d) Avoid the channeling of water to soil measurement plots.
    e) Avoid trenching in the 1.3 m radius circle centered under the IR skin temperature sensor.

f) Place soil on tarp, and put back in the order it was removed at the same level. Use this method for trenching near the plots, too; put the soil on a tarp and backfill in the place of origin.
g) When labeling an installation site map with the location of newly installed soil probes, mark areas where future soil probes can be added to replace old ones, label existing trenching, and determine the typical paths of foot traffic so soil probes are not placed in compacted soil.

4) Placement of soil probe plots

a) Avoid shading by installed equipment where possible.
b) Avoid steep terrain where possible.
c) Avoid standing water.
d) If possible, utilize high resolution soil maps to choose representative soils. Take push probe samples to see what soil is like at the plots. When available, utilize the expertise of a USDA soil extension person when installing to identify soil accurately in field and take samples.
e) Coordinate with USDA Gary Schaefer or Deb Harms to provide a USDA contact to meet installation crew in the field for soil probe installs.
f) Gary or Deb are willing to come out and consult directly on the first 1-5 installations to make sure all procedures are sound, especially the acquisition of soils metadata.
g) Desktop planning should be done before each soil probe deployment, including giving USDA an accurate latitude/longitude for preliminary soils identification on maps or in databases. Site photographs and station installation diagrams should be examined to predetermine candidate plot locations before going into field.

5) Issues of a generic nature

This conversation started with a brief discussion of probe types, but this topic was deferred to a later point when we would talk about test beds. It was also mentioned in passing that all these suggestions above and below need to be written into a generic procedure document to guide the installers. Finally, site hosts need some relevant information and need to be aware of the installation, not only at the site technical contact level, but also at the site host level.

METADATA FOR SOILS

1) General site characteristics

a) Determine the slope and aspect of site and soil probe plots.
b) Describe the vegetation surrounding plot and land use/land cover in the broad area (~40 km^2) around the site. Include comments on the seasonal cycle of changes, possibly including NDVI changes with season.
c) Note the general landforms at the site location.

d) Record the angles and distances of the soil probe plots very accurately on a polar diagram (like the site obstruction diagram, but at a finer scale).
e) Report the existence of any tile, fill, or other human alterations that could impact soil drainage and/or water tables.
f) Discuss any historical land uses from the past that might have impacted the soils.
g) Add any cyrospheric information that is available, such as snow covered period, etc.

2) Soil characteristics

a) Follow national standards from USDA for soils metadata, available from Deb Harms. This is a long list of properties derived from the lab analyses of soils (like water retention curves) and from the field observations.
b) Use existing standard operating procedures for gathering soils samples in the field, including clod samples, core samples, and a physical description of soil in a pit wall by a trained soil expert.
c) Collect ground truth, both at time of install and other times, using a probe to gather gravimetric samples.
d) Summarize the rock content of the soil, both at the surface and through the soil core.
e) If possible, measure soil thermal characteristics, such as heat capacity, thermal conductivity, and thermal diffusion.
f) Note the water table, if found above 1 m, or if available from a nearby well.

DATA SAMPLING

A discussion of sampling for soil moisture measurements led in a variety of directions.

1) Averaging periods versus number of independent samples

a) Several speakers felt that soil moisture should be averaged over a long enough period to suppress noise, but still be a measure at a moment (albeit a long moment) rather than an average over a hour. Other speakers felt it was o.k. to average over periods, using a number of individual samples.
b) Example: Oklahoma samples every 20 seconds and transmits 15 minute averages.
c) Examples: Bob Z. and Steve O. save 1 or 2 minute soil moisture data.
d) Example: Tom J. indicated that field campaigns retain high resolution soil moisture data to insure a time match with remotely sensed data.

2) Current sampling intervals/issues with USCRN equipment

a) The fastest the USCRN soil moisture probe installation can sample soil moisture and temperature for 15 probes is about 2 minutes.
b) In the test bed, we are currently reporting hourly averages of 2 minute observations.
c) Bob Z. showed some examples where Hydra II probes had large moisture diurnal cycles in the desert due to the temperature sensor not handling heat greater than +40°C and a correction based on temperature not working well.

3) An option is discussed to transmit both an hourly average and an individual instantaneous measurement for the last 2 minutes before the top of the hour. This was promising and led to a discussion of options in (4) and (5).

4) Ideally, given the USCRN systems and the needs of satellite groups, it was decided that it would be ideal if 12 5-minute samples could be collected for three variables: 5-cm soil moisture, 5-cm soil temperature, and surface (skin) IR temperature. The engineers will be asked to ascertain whether this is possible given the time allotted for GOES data transmission. If the data cannot be loaded into the transmitter buffer in time for sites that transmit early in the hour, there may be a need for an extra hour delay for these sites.

5) All other soil moisture and temperature measurements from the 10, 20, 50, and 100 cm levels will be transmitted as hourly values averaged from 12 samples taken at 5-minute intervals.

WHERE DO WE GO FIRST?

About 40-60 sites will have soil probes installed in FY 2009.

1) Meeting the needs of NIDIS

   a) WY, UT, and CO are fundamental to the Upper Colorado River Basin pilot project, including some site in adjacent ID and AZ.
   b) GA, AL, and western NC sites are associated with the ACT-ACF Basin pilot project. These sites in AL are also close to ATDD, and will likely be targeted first in order to study installation issues and monitor equipment in locations close to ATDD.
   c) Northern WA, MT, and ND sites near the Canadian Border, and, in the case of the first two states, in the Columbia River Basin. The northern tier sites will contribute to a bilateral agreement with Canada.

2) Co-location between CRN and a new SCAN site in Utah, with a California site in Yosemite, and at Reynolds Creek where ARS has a study area for SMAP. Other CRN sites with co-located soil moisture measurement were Bondville (IL) and Valles Caldera (NM).

3) NIDIS endorses soil moisture equipment going into places where remote sensing groups would gain the most benefit in placed representative of their surrounding areas (homogenous) and where intensive campaigns will be occurring.

INTENSIVE CAMPAIGNS

1) In support of remote sensing and weather/climate soil modeling efforts, intensive campaigns may be organized from time to time. Usually, a workshop brings multiple agencies together to plan campaigns and gather resources. Such campaigns can be done for a CRN propose, such as characterizing heterogeneity/homogeneity and representativeness around sites with soil moisture instruments, or CRN may happen to be where an intensive is planned for other

reasons. Data on IR surface (skin) temperature, 5-cm soil moisture, and 5-cm soil temperature compatible with CRN can be gathered for many locations with 40-50 km^2 around the site. In a remote sensing intensive, many other variables would also be collected.

2) This activity would support NIDIS modeling and remote sensing work for drought detection and characterization.

3) By linking to NEON or other NSF funded projects, this would allow the intensive campaign to receive NCAR support services.

4) The executive council of the GEO directorate may be interested, especially if there is an international component.

5) Linkages to the Climate Program Office through an appropriate RISA could be made.

TESTBEDS

Soil moisture and temperature probes need to be tested and intercompared due to rapidly changing and varied technologies for making these measurements, and the need for continuity with the CRN and when compared to other measurements.

1) A soil moisture/soil temperature testbed can focus on several goals.

   a) New technologies and instruments
   b) International cooperation
   c) Standardization through intercomparison
   d) Establishment of control protocols and test criteria for lab bench tests

2) Set controlled conditions for intercomparisons.

   a) Lab set-ups and media used
   b) Uniformity of soils in sites for outdoors intercomparisons
   c) Use the 10 cm level for outdoor intercomparisons

3) Develop standard procedures for intercomparisons.

   a) Standards for gravimetric sampling as the basis for all comparisons
   b) Within lab comparisons with various substances over a range of dielectric constants, and standard soils, with the same methods
   c) Compare all commonly used probes, along with other new remote sensing technologies like GPS and COSMIC methods

MEASUREMENT QA/QC

A brief conversation was held on QA/QC, with references to a long list of possible tests that can be found in Bill Collins talk, slide #2. The conversation is discussed below, but without this list.

1) Freezing conditions require any soil moisture data that is transmitted to be set to missing.

    a) The dielectric of the soil rapidly declines with freezing, as the water is no longer detected when it converts to crystalline form.
    b) The dielectric is affected even when ice forms near the instrument, not just between the tines of the probe.

2) Chris F. of the OK Climate Survey has published an extensive review of soil moisture QC.

3) Most people attending will toss out outliers, which are thought to be generated by RF interference. Some manually remove outliers, while others run automated filters to clean the data.

4) Since the CRN is taking three measurements, it is definitely worthwhile to report with the average or median of the three measurements the standard deviation. Given the uncertainty in soil differences between the three plots, many in the room favored averaging over taking the median for the layer value for a site.

5) The Bill Collins QC list (filters, spike tests, etc.) would likely be applied to the individual measurements before the QC tests on the pairwise differences between probes at the same level.